

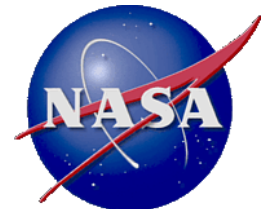


# Orion Spacecraft MMOD Protection Design and Assessment

**APS Shock Physics Conference, Chicago, IL  
June 29, 2011**



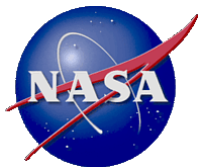
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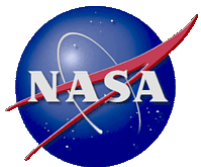
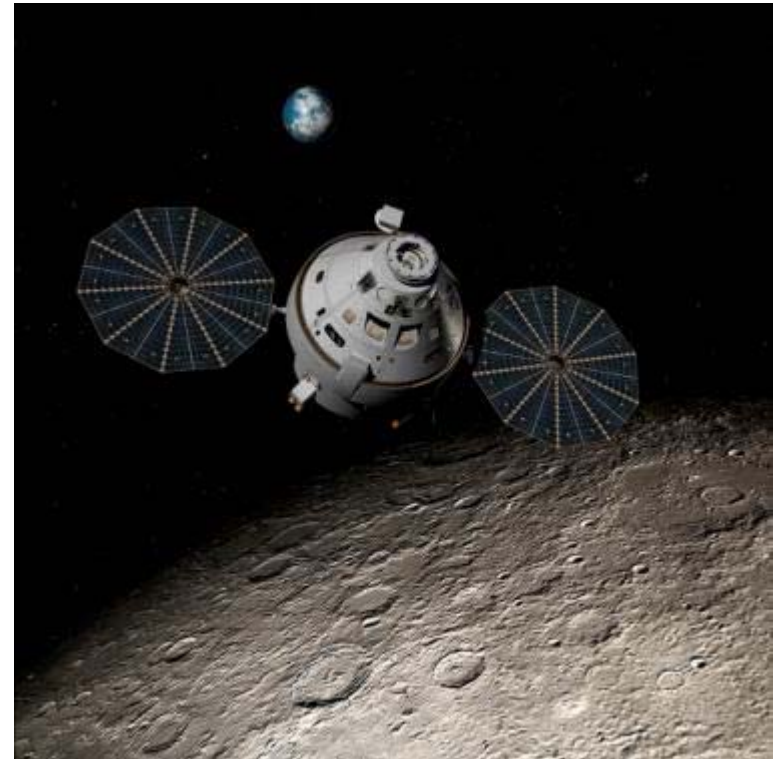
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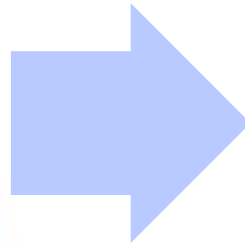
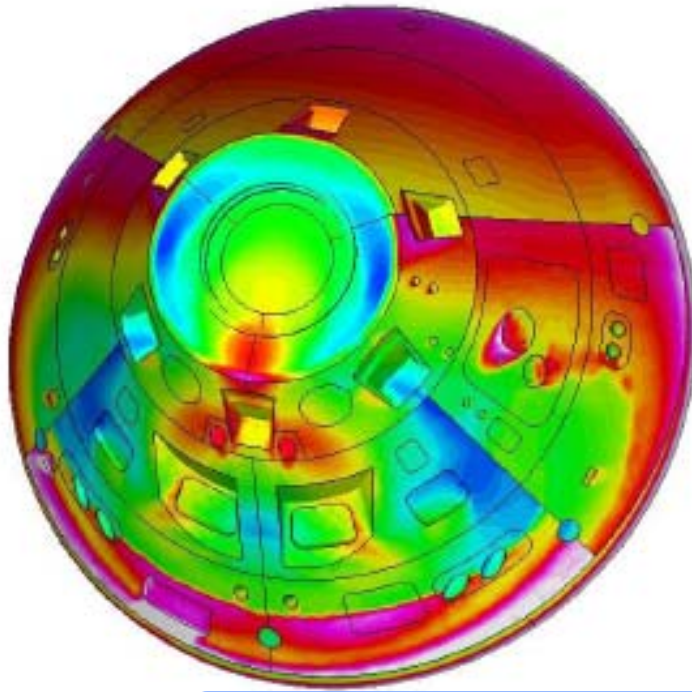
# **A first-principals, semi-empirical ballistic performance model has been developed for porous ceramics**



- **Lightweight thermal protection systems protect the crew and vehicle of orbital and exo-orbital missions from the intense heat of atmospheric reentry**
- **To maintain low launch weights these materials are their own protection from space hazards like orbital debris and meteoroids**
- **A ballistic performance model is described here that models the performance under a variety of impact conditions**

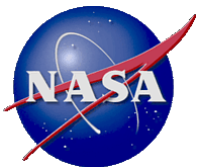


# Atmospheric braking creates high surface temperatures that must be mitigated



- The Orion thermal protection system surfaces can be heated by the reentry plasma to temperatures above 1000 °K creating thermal gradients of several 100 °K over their thickness

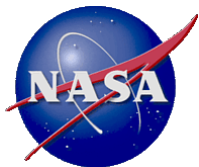
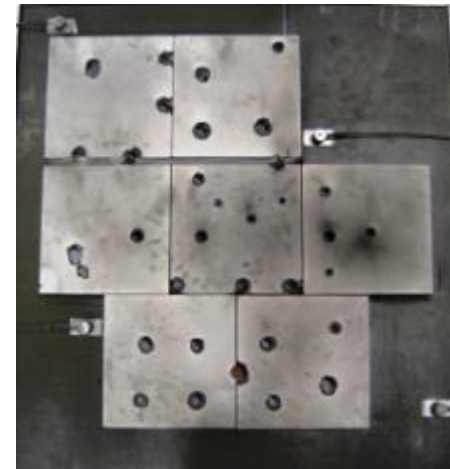
- The small dimensions of high probability impacts afford some damage tolerance due to limited thermal convection in the small cavities leaving the residual insulation as the key performance parameter



# Tests of Orion thermal protection tiles are used to establish the thresholds of failure

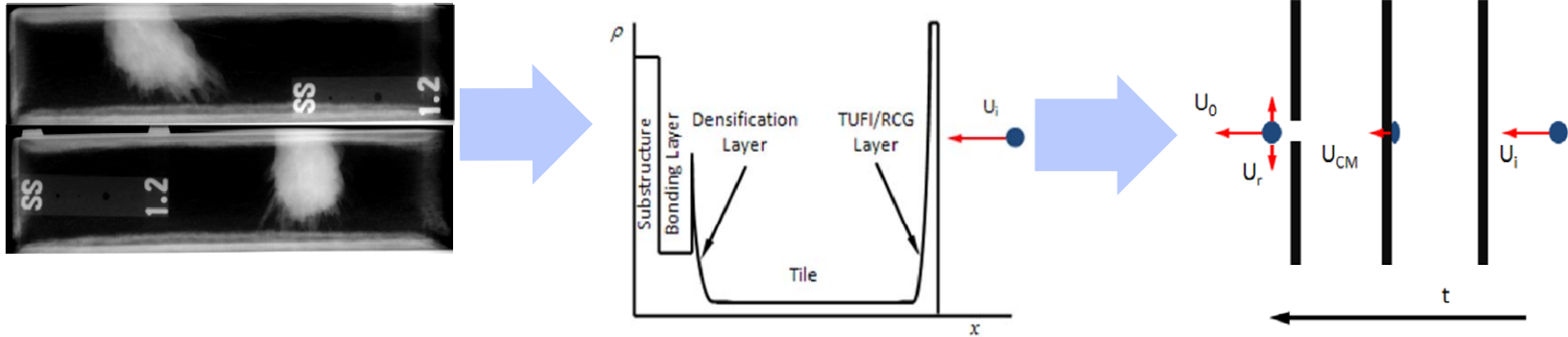


- AETB8 impacts have performed by Orion program at:
  - UDRI with maximum velocities of ~10 km/s
  - WSTF with maximum velocities of ~8.5 km/s
- 50 internal tile damage impacts have been performed
  - Impactors include Nylon, Aluminum and Steel
  - Impact obliquities from normal to 75° to normal
  - Impact velocities from 3 to 10 km/s
  - 2 different areal densities of hard outer layer





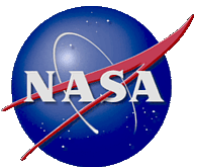
# Impacts on tiles involves a sequence of densities that distribute impact energy



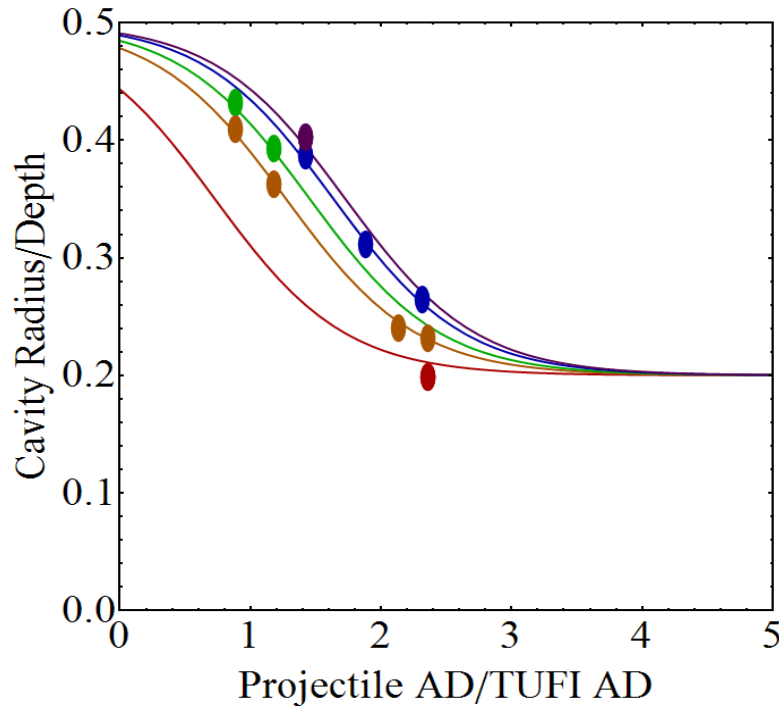
- Projectile impacts the higher density TUF/RCG layer and creates a cavity as it goes through the lower density tile

- The density profile:
  - High density TUF/RCG layer
  - Low density tile
  - Higher density silica layer and bonding layer

- Projectile slows to equilibrium in the TUF/RCG layer and then releases to an initial velocity,  $U_0$ , and a lateral release velocity,  $U_r$ , in the tile



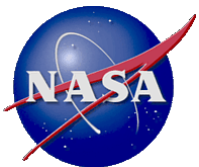
# A modified logistics function reproduces the ratio of cavity depth to half-width



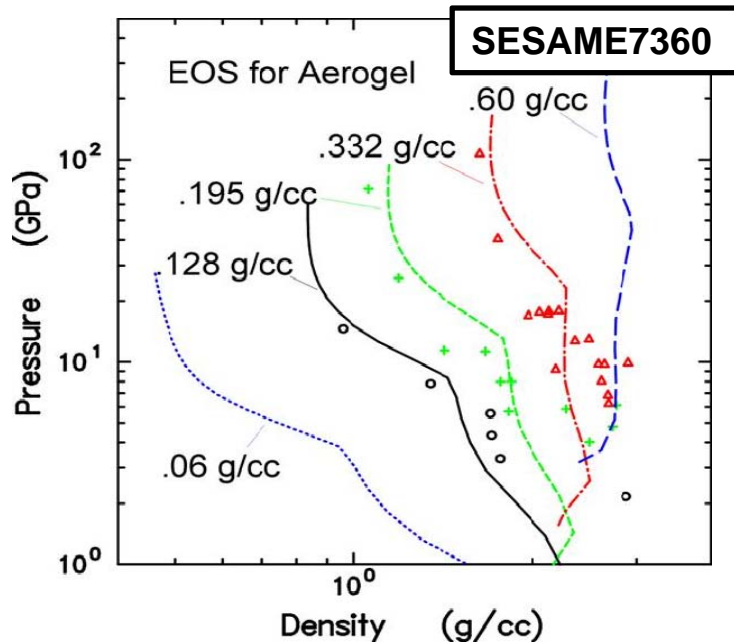
- Points are shot data color coded to the corresponding velocity bin (km/s): 4 (red), 7 (orange), 8 (green), 9 (blue), 9.5 (magenta)

$$\omega = \frac{\delta\omega}{\text{Exp} \left[ \frac{\overline{m}_p U_m - \overline{m}_T U_i}{1/2 \overline{m}_T U_m} \right] + 1} + \omega_0$$

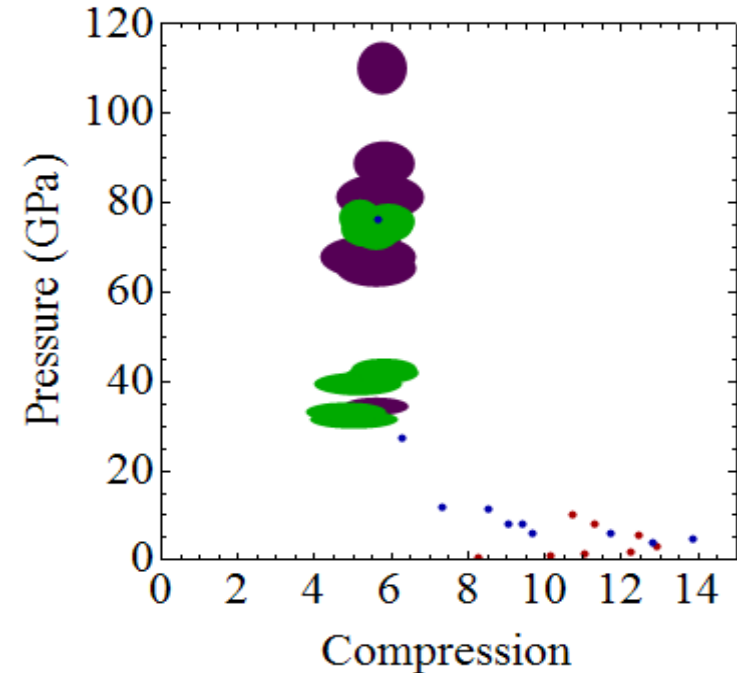
- Empirical relation
- Fit parameters:
  - $\delta\omega$  is 0.3
  - $\omega_0$  is 0.2
  - $U_m$  is 5.5 km/s
- Represents fraction of dispersed projectile and TUFI to large fragments
  - First term numerator is the product of required pressure and time in projectile for break up
  - Second term numerator is the product of induced pressure of the impact and time to rarefaction generation
  - Denominator is the dispersion of pressure and time about the required



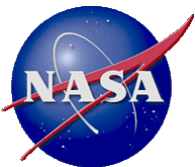
# EOS studies show approximately isochoric behavior in jump states of porous silica



- N. C. Holmes and E. F. See in Shock Waves of Condensed Matter of 1991 with a SESAME 7360 P- $\alpha$  compaction of 2.5 GPa for  $P_s$  overlaid

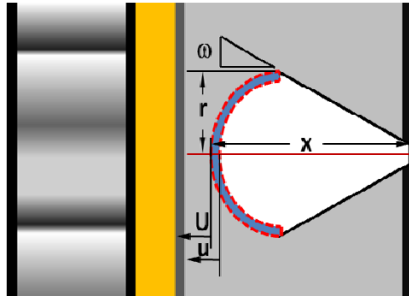


- T. R. Boehly, *et al.* in Shock Waves of Condensed Matter of 2007 extended silica aerogels to much higher pressures indicating continual significant energy sinks





# Mass, EOS and momentum equations combine to a 1st order differential



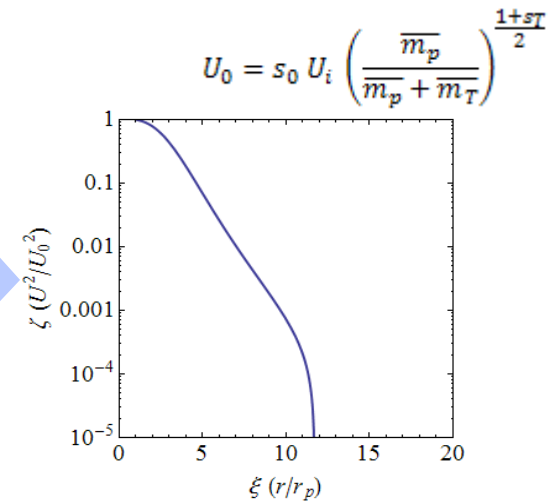
$$\frac{dMu}{dt} = \frac{M}{s_0} \frac{dU^2/2}{dx} = -F_H - F_M$$

$$F_H = \rho_0 \left( \frac{U^2}{s} + \frac{\rho}{\rho_0} \left( \frac{U}{s} - U \right)^2 \right) A$$

$$F_M = Y_0 A$$

$$M = \left( \frac{4\rho_p r_p}{3} - \frac{\rho_0 r_p/\omega}{3} \right) \pi r_p^2 + \frac{\rho_0 A x}{3}$$

$$\frac{1}{s_0} \left( \frac{\mu - 1/3}{\xi^2} + \frac{\xi - 1}{3} \right) \frac{d\xi}{d\xi} + \frac{s_0 + 1}{s_0} \xi = -\psi$$

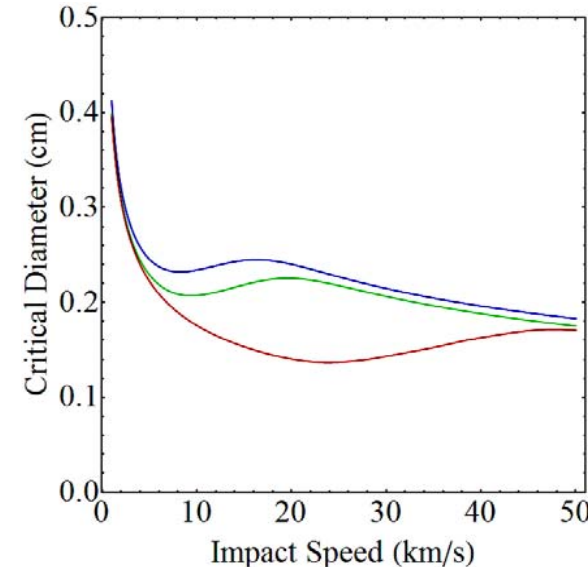
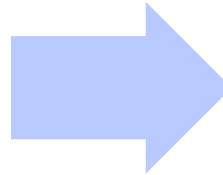
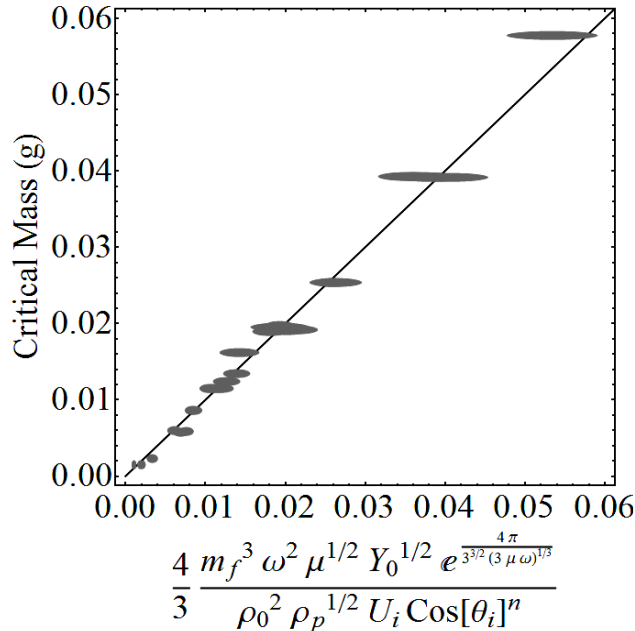


- The disrupted projectile expands as it traverses the tile scattering increasing mass to slow faster than a fully intact projectile does

- The non-dimensional Lagrangian form of the mass, EOS and momentum equations (see Appendix of accompanying paper for full derivation)

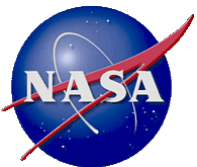
- The normalized equation for projectile velocity decreases rapidly under expansion until the strength of the tile finally arrests the projectile

# Model reproduces the tests performed and shows evidence of a double wall behavior

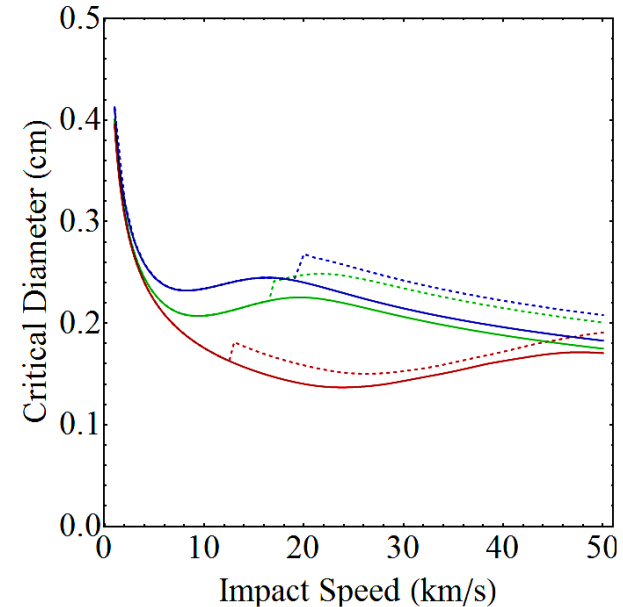
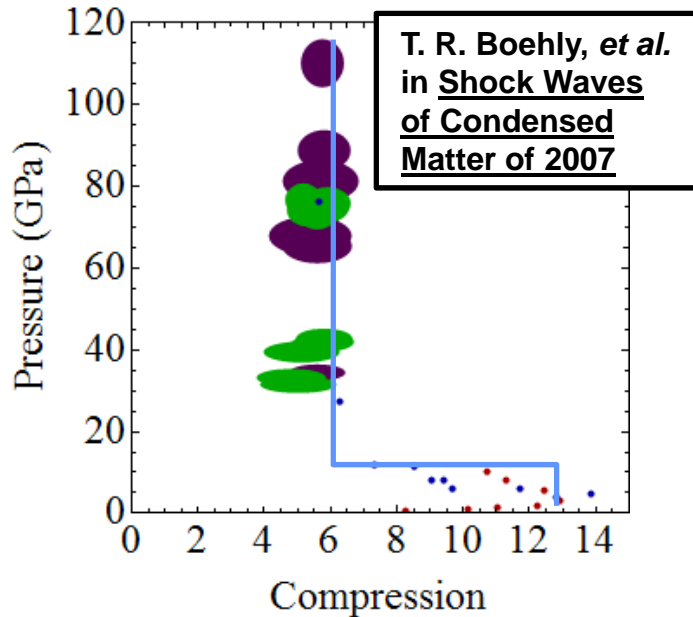


- Simplified solution of the model reproduces
  - Nylon, aluminum and steel projectiles
  - Impact obliquities to 75° to normal
  - Impact velocities to 10 km/s
  - Light and Heavy TUF/RCG

- Model shows the double wall effect of fragmentation/melt of impactors
- Shows the dependence of the onset of fragmentation/melt of impactors on weight of TUF/RCG layer

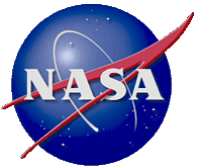


# Higher impedance at high shock wave strengths may also increase performance

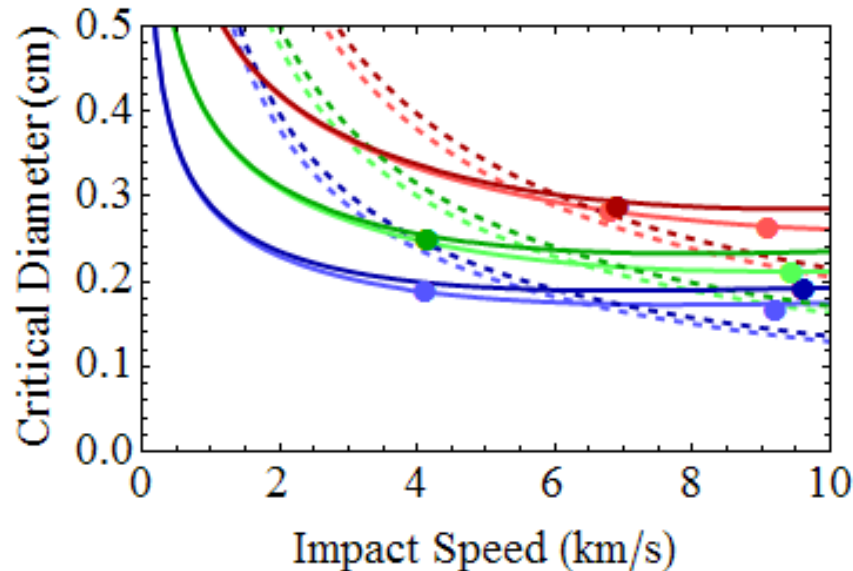


- Equation of state measurements show that below ~10 GPa a porous silicates compress to near solid density and experiences a ~6x compression above
- This behavior can be approximated with a piecewise shock wave slope

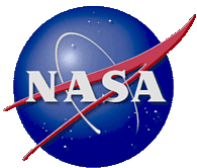
- Higher impedance could result in higher performance at higher impact speeds typical of meteoroids
- Onset is at lower impact velocities for lighter outer layers



# The implemented ballistic limit equation lowers risk predictions considerably



- Predicted risk associated with this model relative to an energy scaled model is 60% lower for orbital debris and 95% lower for meteoroids at ISS orbital parameters



# A first-principals, semi-empirical ballistic performance model has been developed for porous ceramics



- Lightweight thermal protection systems protect the crew and vehicle of orbital and exo-orbital missions from the intense heat of atmospheric reentry
- To maintain low launch weights these materials are their own protection from space hazards like orbital debris and meteoroids
- A ballistic performance model is described here that models the performance under a variety of impact conditions
- Using the model described here relative to an energy scaled model results in a significantly reduced prediction of full penetration of this material at ISS orbital parameters

